International Journal of Scientific Engineering and Technology ISSN :2277-1581
Volume No.4 Issue No.8, pp: 432-437 01 August 2015

Optimal Design and Feasibility Study of Renewable Hybrid Energy Systems

Sayantani Dey[1], Samrat Malakar[2]
Associate Members, The Institution of Engineers (India)

Abstract : Of the 1.24 billion people in the country, more than 450 million people do not have access to electricity as well as over 95,000 villages still remain dark after sunset. Even the electrified villages suffer power cuts of 15 hours or more on a daily basis. These problems compel us to resort to other energy sources that are inexhaustible. The paper proposes analysis and comparative study of Hybrid Renewable Electric System, especially Photovoltaic-Fuel cell hybrid system, Wind-Fuel cell hybrid system and Photovoltaic-Wind-Fuel Cell hybrid system with Hybrid Optimization Model for Electric Renewable (HOMER) software for distributed generation system. The model simulates all the above small power technologies in hybrid configurations to identify the optimum hybrid system with minimal cost for remote residential loads in the Sunderbans, India.

Keywords – Solar Photovoltaic, Wind Turbine, Fuel Cell, HOMER, Cost of Energy.

I. INTRODUCTION

Keeping in view the present energy scenario in India, it has become absolutely necessary to switch to alternative sources of energy like solar, wind, small hydro, fuel cell and biomass for satisfying the ever-increasing energy demand, especially in the rural areas, where grid connectivity is not practically feasible. The existence of problems in electricity transmission in remote regions as well as its high cost, force us to resort to other energy sources that are inexhaustible. Due to the intermittent nature of solar irradiation and wind speed, solar-wind hybrid energy system often fail to meet the peak demand.

Substantial research work on this field has been found in the literature. The coordination control problem for a hybrid distributed energy generation system consisting of a PMSG,PV array and a proton exchange membrane fuel cell (PEMFC) stack to supply continuous power to the stand-alone loads has been investigated by Xiao Li et al. [1]. A methodology for cost minimization of a stand-alone hybrid energy system including PV arrays/wind turbines/fuel cells through the overall 20-years life time of the system by considering reliability constraints has been postulated by Sajjad Abedi et al. [2] in their paper. Differential evolutionary algorithm is employed to solve the mixed integer nonlinear optimization problem. Milana Trifkovic et al. [3] propounded system integration and controller design for power management of a stand-alone renewable energy hybrid system in Lambton College, Ontario, Canada. A hierarchical control system consisting of a supervisory controller and local controllers for the PV, wind, electrolyzer and fuel cell units is implemented. A scheme to integrate different sources of energy into a hybrid energy system consisting of wind generator, PV arrays, a fuel cell and an ultra-capacitor bank for stand-alone power applications has been presented by C. Patsios et al. [4].The system operation is highly influenced by the supply-demand equilibrium and takes into account issues of fuel cell long-term durability and actual constraints regarding electrolyzer operation and energy efficiency considerations. Mohan Kolhe et al. [5] probed a feasibility study of an off-grid hybrid renewable energy system for supplying electricity to a rural community in Siyambalanduwa region in Sri Lanka. Optimum sizing of each component in the PV, wind, battery and diesel generator hybrid system is done using the HOMER software. A multi-input power converter (MIPC) consisting of a dc-dc converter and a dc-ac inverter for hybrid PV array, wind turbine, proton exchange membrane fuel cell (PEMFC) and battery storage (BT) connected to AC grid network has been put forward by M. A. Rosli et al [6] where P&O method is mainly used to accomplish the maximum power point tracking (MPPT) algorithm for PV array.

For the proposed hybrid systems, the meteorological data of wind speed and solar radiation is taken for the Sunderbans, West Bengal, India (Latitude 21.9450°'N and Longitude 88.8958°E) and the pattern of consumption of remote residential load profiles are studied and suitably modelled for optimization of the hybrid system using Hybrid Optimization Model for Electric Renewable (HOMER) software. This model analyzes the options for providing power to a remote residence. The main source of power is Photovoltaic and Wind turbine system, the storage backup system is a battery bank and a hydrogen storage fuel cell system. Cost analysis of each proposed configuration is then carried out to determine the minimal cost system.

II. SYSTEM COMPONENTS

A. Photovoltaic panel

The power output of solar panels at Maximum Power Point (MPP) is given by:

$$P_{PV} = V_{mpp} * I_{mpp} \quad (1)$$
$$V_{mpp} = V_{mpp,refr} * V_{oct} (T_p - T_{p,refr}) \quad (2)$$
$$I_{mpp} = I_{mpp,refr} * I_{sct,refr} (T_p - T_{p,refr}) \quad (3)$$

Where, P_{PV} is the panel's power, V_{mpp} is the potential voltage, $V_{mpp,refr}$ is the V_{mpp} at standard condition (V), I_{mpp} and $I_{sct,refr}$ are the current at MPP and short circuit current of the panel at STC respectively and V_{oct} is the open circuit voltage temperature coefficient (V/°c). $T_{p,refr}$ is the panel temperature at STC (25°C) and T_p is the working temperature of the panel given by:

$$T_{p(t)} = T_{a(t)} + \frac{NOCT - 20}{800} G_T \quad (4)$$

Where, $T_{a(t)}$ is the panel's ambient temperature (°C), NOCT is the Nominal Operating Cell Temperature for solar irradiation of 500 W/m^2 and 20°C temperature, and G_T denotes average daily solar irradiation (W/m^2).
Monthly clearness index and radiation for given location is shown in Table I.

International Journal of Scientific Engineering and Technology ISSN :2277-1581
Volume No.4 Issue No.8, pp: 432-437 01 August 2015

TABLE I. MONTHLY SOLAR RADIATION

Month	Clearness Index	Radiation ($kWh/m^2/day$)
January	0.633	5.460
February	0.634	5.940
Mar	0.630	6.390
April	0.562	5.930
May	0.508	5.350
June	0.371	3.870
July	0.355	3.710
August	0.389	4.080
September	0.473	4.830
October	0.475	4.540
November	0.531	4.650
December	0.593	4.990

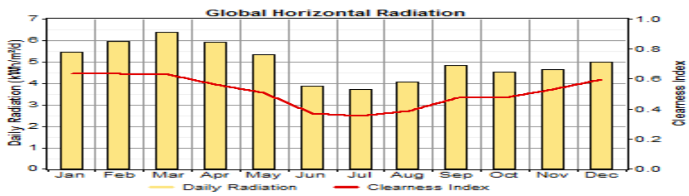

Fig. 1. Solar resource

B. Wind Turbine

At height 'h', the wind speed is given by:

$$V_{t0} = V_{rt0}\left(\frac{h}{h_p}\right)^p \qquad (5)$$

Where, V_{rt0} is the wind speed at height of h_p and p is the power-law exponent (0.14 to 0.25). Accordingly, the output power of the turbine, $P_{wt(t)}$, as follows:

$$P_{wt(t)} = \begin{cases} av^3(t) - bP_R & V_{cin} < V < V_{rt} \\ P_R & V_{rt} < V < V_{cout} \\ 0 & \text{otherwise} \end{cases} \qquad (6)$$

Where, $a = \frac{P_R}{(V_{rt}^3 - V_{cin}^3)}$, $b = \frac{V_{cin}^3}{(V_{rt}^3 - V_{cin}^3)}$

and P_R is the the wind turbine rated power and V_{cin}, V_{rt}, V_{cout} are the cut-in, rated and cut-out wind speed of the wind turbine, respectively.

In this model Generic 10kW wind turbine is used. The estimated lifetime is 15 years and hub height is 25 meters. The monthly available wind speed of study region is shown in Table II.

TABLE II. MONTHLY WIND SPEED DATA

Month	Wind Speed (m/s)
January	3.75
February	3.28
Mar	3.44
April	3.25
May	3.56
June	5.46
July	5.51
August	5.23
September	3.78
October	3.11
November	3.49
December	4.32

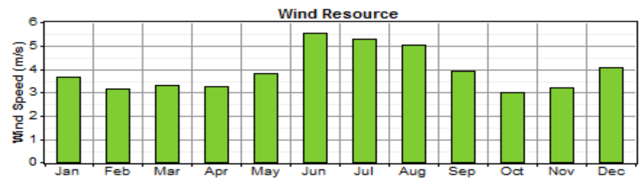

Fig. 2. Wind resource

C. Hydrogen storage fuel cell

Fuel Cell (FC) is available in different configurations, power ranges, type of electrodes and operating characteristics. PEMFC basically contains two electrodes, the anode and the cathode, separated by a solid membrane. Excess available power goes to an electrolyzer which produces hydrogen gas, which in turn goes to a storage tank for consumption by the fuel cell as and when required. Air is continuously fed to the cathode and hydrogen to the anode. The internal chemical reaction is :

$$H_2 + \frac{1}{2}O_2 \longrightarrow H_2O \qquad (7)$$

The consumption of hydrogen during a period of one hour at rated power P_{FC} kW is given by,

$$HY_{FC} = [\,(P_{FC} * 3600) / (2V_{FC} * F\,)] \qquad (8)$$

where,

HY_{FC} = the amount of hydrogen consumed by FC
P_{FC} = output power of FC
V_{FC} = output voltage of FC

D. Electrolyzer

Hydrogen gas can be produced by the decomposing water into its rudimentary constituents by passing electrical current through the electrolyzer. Multiple cells are connected in series in a water electrolyzer whose electrodes are separated by an electrolyte. Decomposition of water into hydrogen and oxygen takes place as per the following equation :

$$H_2O + \text{electricity} \longrightarrow H_2 + \frac{1}{2}O_2 \qquad (9)$$

According to Faraday's law, amount of hydrogen produced by P_{FC} kW electrolyzer in one hour can be calculated as per :

$$HY_{ele} = [(P_{ele} * 3600) / (2 * V_{ele} * F)] \quad \text{mole/h}^{-1} \qquad (10)$$

where, HY_{ele} = amount of hydrogen produced by electrolyzer
P_{ele} = rated power of electrolyzer
V_{ele} = working voltage of electrolyzer

E. Hydrogen tank

During times of excess supply, hydrogen gas produced by the electrolyzer provides a medium for storage of surplus solar energy. The energy stored in the hydrogen tank is calculated by:

$$E_{tank}(t) = E_{tank}(t-1) + (P_{EL\text{-}tank}(t) * \Delta t) - (P_{tank\text{-}FC}(t) * \Delta t * \eta_{storage}) \quad (11)$$

Where, $P_{tank\text{-}FC}$ is the power transferred from the hydrogen tank to the fuel cell, Δt denotes simulation step time and $\eta_{storage}$ is the storage efficiency of the system (~95%). The mass of stored hydrogen, at any time step t, is calculated as follows:

$$M_{storage}(t) = \frac{E_{storage}(t)}{HHV_{H2}} \quad (12)$$

where, the Higher Heating Value (HHV_{H2}) of hydrogen is equal to 39.7 kWh/kg.

F. Battery

Due to the stochastic nature of photovoltaic system, energy storage is needed to supply the load on demand by storing energy during periods of high bright sun. When the total output of the PV array is more than the energy demand, the battery bank is charged.
The imported power in battery is calculated by:

$$\Delta P(t) = P_{ren}(t) - P_L(t) \quad (13)$$

where, $P_{ren}(t)$ is the total energy that has been generated by renewable resources and $P_L(t)$ is equal to:

$$P_L(t) = \frac{P_{Load}(t)}{\eta_{inv}} \quad (14)$$

where, $P_{Load}(t)$ is the desired power and η_{inv} is the efficiency of the DC/AC converter.

The Trojan T-105 battery parameters used in the proposed system is shown in Table 5.

TABLE III. BATTERY PARAMETERS

Properties	T-105 Battery
Nominal Capacity	225 Ah
Nominal Voltage	6 V
Round trip efficiency	85%
Minimum state of charge	30%
Maximum charge rate	1 A/Ah
Maximum charge current	11 A
Float life	10 yrs
Lifetime throughput	845 kWh

G. DC-AC Converter

It is employed to convert the DC power generated by a hybrid system into AC power with desired frequency. The amount of power injected to the load by converter is given by,

$$P_{inv\text{-}Load} = (P_{FCinv} + P_{Ren\text{-}inv}) * \eta_{inv} \quad (15)$$

where, η_{inv} is the inverter's efficiency (~90%).

III. LOAD PROFILE

A stand alone load consuming 3 kWh of energy per day and 472 W_p is considered for analytic study. The hourly load profile and seasonal data are shown in Fig. 3 and Fig. 4 respectively. Both these data are presumed to remain constant during each hour.

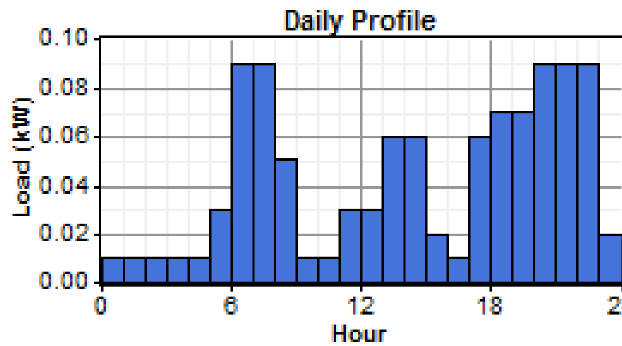

Fig. 3. Daily load profile

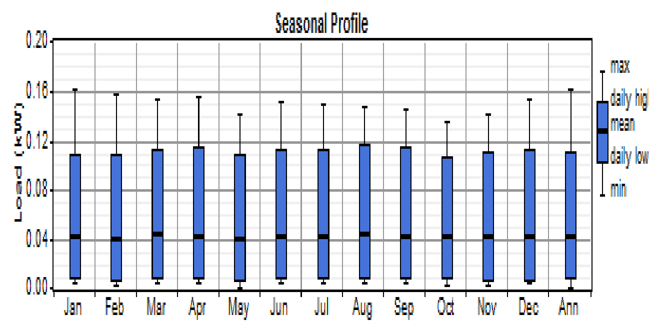

Fig. 4. Seasonal load profile

IV. METHODOLOGY

The HOMER Software tools help in the dealing of optimization, modelling and simulation of the proposed system. Here we are proposing three different models for study. Cost summary of proposed systems is shown in table IV.

TABLE IV. COST SUMMARY

Component	Rating	Capita Cost ($/unit)	Replacemen Cost ($/unit)	O&M Cost ($/yr)	Lifetim (years)	η (%)
PV Panel	1 kW	7000	6000	20	20	13
Wind Turbine	10 kW	19400	15000	75	15	-
Electrolyzer	1 kW	2000	1500	25	20	85
Hydrogen Tank	1 kg	1300	1200	15	20	-
Fuel Cell	1 kW	750	600	219	5	50
Battery	6 V, 225 Ah	150	150	10	10	85
Converter	1 kW	800	750	8	15	90

A. Photovoltaic-Fuel Cell Hybrid System

Case A proposes a hybrid renewable energy system which consists of Solar Photovoltaic arrays, hydrogen storage fuel cell and battery (Fig. 5). Main source of power is Photovoltaic and the storage

ISSN :2277-1581
01 August 2015

backup systems are a battery bank and a hydrogen storage fuel cell system. The life time of this system is assumed to be 20 years.

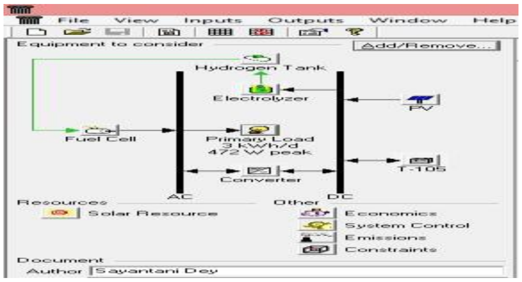

Fig. 5. HOMER model of Photovoltaic-Fuel Cell hybrid system

B. Wind-Fuel Cell Hybrid System

For Case B, hybrid renewable energy system components are Generic 10 kW wind turbine, Hydrogen storage Fuel cell and Battery (Fig. 6). In this case main source of power is wind turbine. Storage backup system used here is a battery bank and a Hydrogen storage fuel cell system. Rated power of wind turbine is 10kW and the hub height is 25 meters.

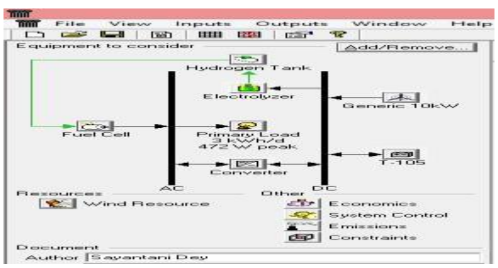

Fig. 6. HOMER model of Wind-Fuel Cell hybrid system

C. Photovoltaic-Wind-Fuel Cell Hybrid System

For Case C, hybrid renewable energy system components are solar photovoltaic arrays, a Generic10 kW Wind turbine, a Hydrogen storage Fuel cell and a Battery (Fig. 7). In this case main source of power is solar PV energy and wind turbine. Storage backup system used here is a battery bank and a Hydrogen storage fuel cell system.

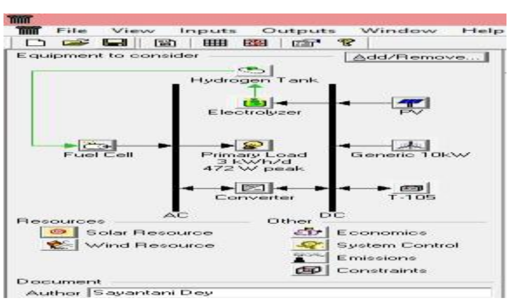

Fig. 7. HOMER model of Photovoltaic-Wind-Fuel Cell hybrid system

V. SIMULATION RESULTS

1) Case A

The optimization result of the Photovoltaic-Fuel cell Renewable Hybrid System is shown in Fig. 8, which shows the optimized unit size and number of required units of each component in the proposed system. Fig. 9 shows the result of monthly average electric production simulation.

	PV (kW)	FC (kW)	T-105	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	FC (hrs)
	2.0	0.1	8	1.0	0.5	1	$ 18,375	353	$ 21,141	2.473	1.00	0.01	588

Fig. 8. Optimization result for Photovoltaic-Fuel Cell hybrid system

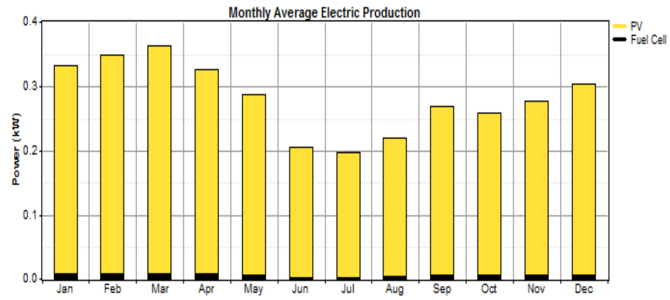

Fig. 9. Simulation result for PV-Fuel Cell hybrid system

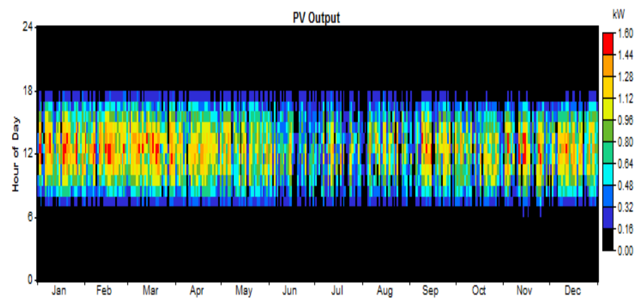

Fig. 10. PV cell output simulation result

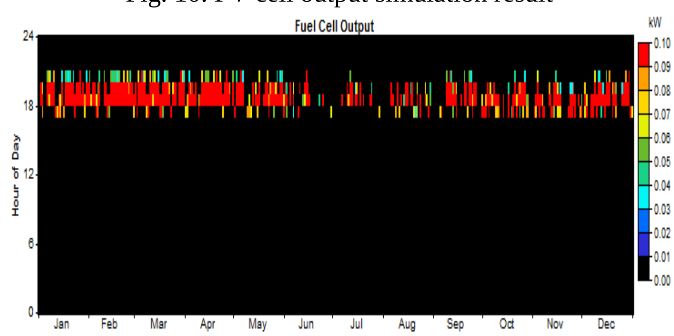

Fig. 11. Fuel cell output simulation result

2) Case B

The Optimization results of Wind-Fuel hybrid system is shown in Fig. 12. It shows the optimal unit size and number of units of each component in this system. Fig. 13 shows the monthly average electric production simulation result. Fig. 14 and Fig. 15 show the wind turbine output and fuel cell output results.

ISSN :2277-1581
01 August 2015

G10	FC (kW)	T-105	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	FC (hrs)
1	0.1	24	0.5	1.5	1	$ 31,450	1,512	$ 50,785	3.628	1.00	1,006

Fig. 12. Optimization result for wind fuel cell hybrid system

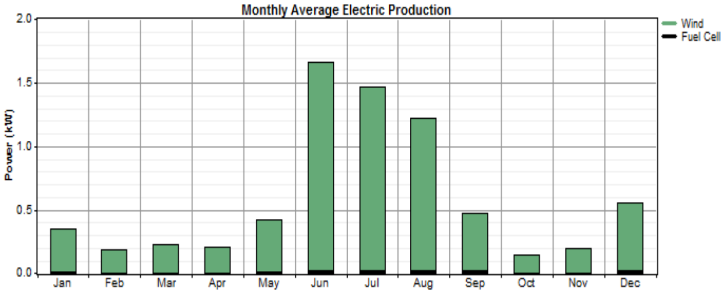

Fig. 13. Simulation result for wind fuel cell hybrid

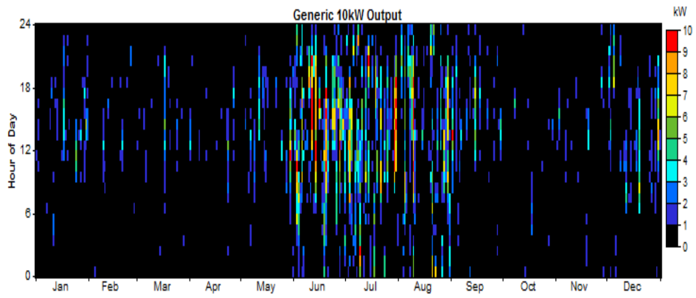

Fig. 14. Wind turbine output simulation result

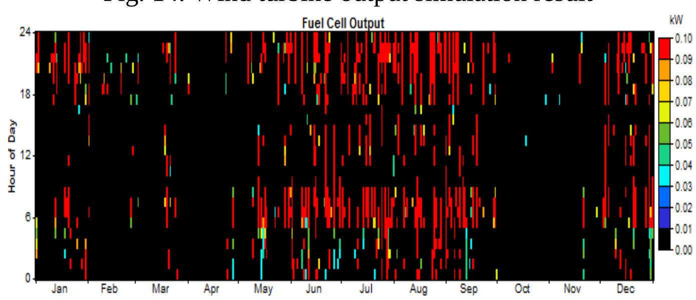

Fig. 15. Fuel cell output simulation result

3) Case C

The Optimization results of Photovoltaic Wind-Fuel Cell hybrid system shown in Fig. 16 reveals the optimized unit size and number of units of each component in this system. Fig. 17 shows the monthly average electric production simulation result. Fig. 18, Fig. 19 and Fig. 20 show the PV panel output, Wind Turbine output and Fuel cell output results respectively.

PV (kW)	G10	FC (kW)	T-105	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	FC (hrs)
0.5	1	0.1	8	1.0	1.0	1	$ 29,475	931	$ 41,373	2.956	1.00	1,278

Fig. 16. Optimization result for photovoltaic wind fuel cell hybrid system

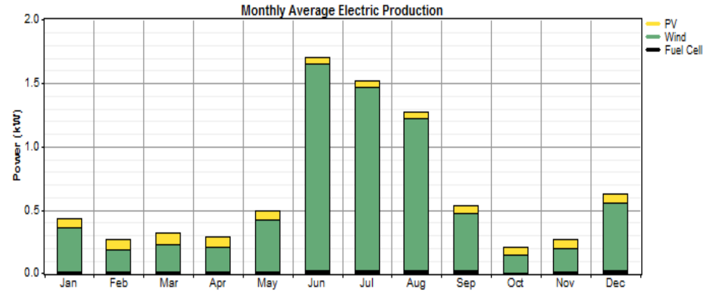

Fig. 17. Simulation result for PV-Wind-Fuel Cell hybrid system

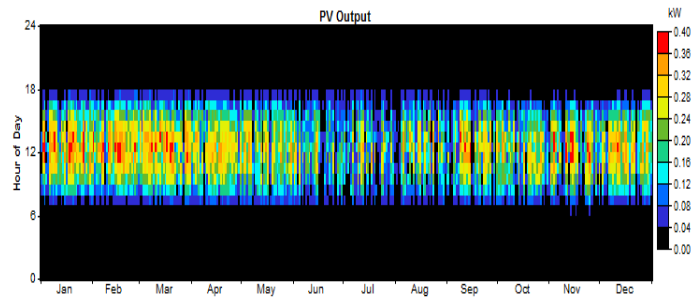

Fig. 18. PV cell output simulation result

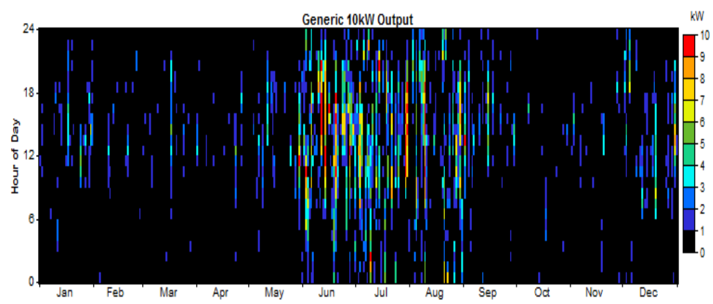

Fig. 19. Wind turbine output simulation result

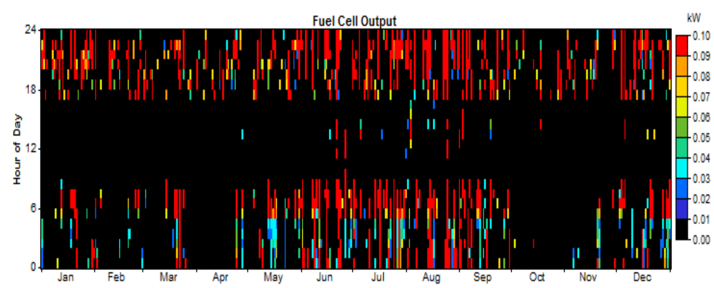

Fig. 20. Fuel cell output simulation result

VI. OPTIMIZATION RESULTS

The proposed model gives the comparative analysis of Hybrid Photovoltaic-Fuel Cell, Hybrid Wind-Fuel Cell system and Hybrid Photovoltaic-Wind-Fuel Cell system providing power to remote residential loads in the Sunderbans**.** The two possible sources of power are Photovoltaic and Wind turbine system and the two possible storage media are a battery bank and a hydrogen storage fuel cell system. The optimization results, emissions and Electrical Production and Consumption of the proposed renewable hybrid energy systems are shown in Table V, Table VI and Table VII respectively.

TABLE V. OPTIMIZED SYSTEM COMPONENTS

Hybrid RES / Component	Optimized Unit Size		
	Case A (PV-Fuel Cell)	Case B (Wind-Fuel Cell)	Case C (PV-Wind-Fuel Cell)
PV Cell	2 kW	-	0.5 kW
Wind Turbine	-	10 kW - 1 No.	10 kW - 1 No.
Fuel Cell	0.1 kW	0.1 kW	0.1 kW
Battery	8 Nos.	24 Nos.	8 Nos.
Hydrogen Tank	1 kg	1 kg	1 kg
Electrolyzer	0.5 kW	1.5 kW	1 kW
Converter	1 kW	0.5 kW	1 kW

TABLE VI. EMISSIONS (KG/YEAR)

Hybrid RES / Pollutant	PV-Fuel Cell System	Wind-Fuel Cell System	PV-Wind-Fuel Cell System
Carbon dioxide	0.181	0.317	0.376
Carbon monoxide	0.115	0.202	0.239
Unburned hydrocarbons	0.0128	0.0224	0.0265
Particulate matter	0.00868	0.0152	0.018
Sulphur dioxide	0	0	0
Nitrogen oxides	1.03	1.8	2.13

TABLE VII. ELECTRICAL PRODUCTION AND CONSUMPTION

Case A : PV-Fuel Cell System					
Production	**kWh/year**	**%**	**Consumption**	**kWh/year**	**%**
PV Array	2416	98	AC Primary Load	1090	57
Fuel Cell	52	2	Electrolyzer load	822	43
Total	2469	100	Total	1912	100
Case B : Wind-Fuel Cell system					
Production	**kWh/year**	**%**	**Consumption**	**kWh/year**	**%**
Wind Turbine	5111	98	AC Primary Load	1095	43
Fuel Cell	92	2	Electrolyzer load	1442	57
Total	5203	100	Total	2537	100
Case C : PV-Wind-Fuel Cell system					
Production	**kWh/year**	**%**	**Consumption**	**kWh/year**	**%**
PV Array	604	10	AC Primary Load	1095	39
Wind Turbine	5111	88	Electrolyzer load	1714	61
Fuel Cell	106	2	-	-	-
Total	5821	100	Total	2809	100

TABLE VIII. COST ANALYSIS

Hybrid RES / Cost	PV-Fuel Cell System	Wind-Fuel Cell System	PV-Wind-Fuel Cell System
Initial Capital (Rs.)	11,34,289	19,41,409	18,19,492
Operating Cost (Rs./year)	21,791	93,336	57,471
Total NPC (Rs.)	13,05,034	31,34,958	25,53,955
Cost of Energy (Rs./kWh)	153	234	183

VII. CONCLUSION

The proposed model gives the comparative analysis of Hybrid Photovoltaic-Fuel Cell, Hybrid Wind-Fuel Cell and Hybrid Photovoltaic-Wind-Fuel Cell system providing power to remote residential loads in inaccessible areas of the Sunderbans**.** Solar photovoltaic and wind turbine system are the considered sources of power, with a battery bank and a hydrogen storage fuel cell system as the two possible storage media. HOMER simulation results of all the three proposed hybrid systems reveal that for the particular location in the Sunderbans, PV-Fuel Cell hybrid system is more economical and feasible compared to the other two systems, under specific meteorological conditions.

REFERENCES

i. Xiao Li, Xiaohong Jiao and Luhao Wang, "Coordinated Power Control of Wind-PV-Fuel Cell for Hybrid Distributed Generation Systems", SICE Annual Conference 2013, Nagoya, Japan, Sept.14-17, 2013.

ii. Sajjad Abedi, Hani Gharavi Ahangar, Mostafa Nick, Sayed Hossein Hosseinian, "Economic and reliable design of a hybrid PV-wind-fuel cell energy system using differential evolutionary algorithm", 19th Iranian Conference on Electrical Engineering (ICEE), 2011.

iii. Milana Trifkovic, Mehdi Sheikhzadeh, Khaled Nigim, Prodromos Daoutidis, "Hierarchical Control of a Renewable Hybrid Energy System", 51st IEEE Conference on Decision and Control, Dec. 10-13, 2012. Maui, Hawaii, USA.

iv. C. Patsios, M. Antonakopoulos, A. Chaniotis, and A. Kladas, "Control and analysis of a hybrid renewable energy-based power system", XIX International Conference on Electrical Machines - ICEM 2010, Rome.

v. Mohan Kolhe, K. M. Iromi Udumbara Ranaweera, A. G. B. Sisara Gunawardana, "Techno-Economic Optimum Sizing of Hybrid Renewable Energy System", IEEE Transcations On Energy Conversion, Vol 24, Issue 2, 2009.

vi. M. A. Rosli, N. Z. Yahaya and Z. Baharudin, "A Multi-Input Converter for Hybrid Photovoltaic Array/Wind Turbine/Fuel Cell and Battery Storage System Connected AC Grid Network", IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA), 2014.

vii. Daming Xu, Longyun Kang, Liuchen Chang, Binggang Cao, "Optimal Sizing Of Standalone Hybrid Wind/PV Power Systems Using Genetic Algorithms", Canadian Conference on Electrical and Computer Engineering, 2005 , pp. 1722 - 1725.

viii. R. A. Gupta, Rajesh Kumar, Ajay Kumar Bansal, "Economic Analysis and Design of Stand-Alone Wind/Photovoltaic Hybrid Energy System using Genetic Algorithm", International Conference on Computing, Communication andApplications(ICCCA), 2012 , pp. 1 - 6.

ix. J. P. Iuscu , C. R. Ozansoy, "Modelling and Hardware Analysis of a Fuel Cell / Photovoltaic System", Power Engineering Conference, AUPEC, 2009, pp. 1 - 6.

x. Qi Zhiyuan, "Coordinated Control for Independent Wind-Solar Hybrid Power System", Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2012 , pp. 1 - 4.